

SAVING ENERGY AND NATURAL RESOURCE BY MICRO-NANOMACHINING

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ABSTRACT

Micro-nanomachining technologies have been studied with the aim of saving energy and natural resources. Wafer process packaging using electrical feedthrough in glass has been applied to micromechanical sensors as electrostatically levitating micro motors (10,000 rpm) for rotational gyroscopes. Maintenance tools as active catheters have been developed to be used in narrow space for extended life. Technologies for compact power source as fabrication of ceramic microstructures using silicon mold and as measurement of hydrogen storage capacity of carbon nanotube were developed.

INTRODUCTION

Applications of advanced states of the art of micromachining for saving energy and natural resource have been our main research subjects. Miniaturization of large sophisticated systems by MEMS can be effective for this in principle.

Cost effective small volume manufacturing of different kind value-added products are required not only for MEMS devices to be used widely but also for preventing overproduction. Wafer process batch packaging technique using electrical feedthrough in a glass plate has been developed for this purpose.

Micro tools for maintenance are required for minimal invasive medicine and extending machine life. Active catheters and sensors for such purposes have been developed.

Compact power sources as micro gas turbine electrical power generator and micro fuel cell are needed for autonomous robots and wearable information systems. Technologies for the compact power sources have been studied.

Advanced key components can be also contribute to minimize energy consumption. Multiprobe data storage and anticorrosive integrated massflow controller for information systems and manufacturing systems will be described below.

COST EFFECTIVE SMALL VOLUME MANUFACTURING OF MEMS DEVICES

The MEMS foundry and versatile common prototyping facility are effective to share the cost of production and development. Open collaboration system for accessing different technologies and needs efficiently are also important for R&D to minimize the turn around and maximize the risk tolerance.

It is told that packaging is 80% of cost and limiting factor of MEMS devices. Wafer process packaging shown in Fig.1 is effective for small volume production because it makes batch assembly possible and particular automated machines to assemble each chip can be eliminated. The wafer process packaging can be done by an anodic bonding of a silicon wafer and a glass plate[1]. This method has advantages to enable chip size packaging and to protect the MEMS structure during the dicing process. Electrical feedthrough from glass holes plays important roles and has been developed for this.

The wafer process packaging has been applied for many products as integrated capacitive pressure sensor[2], diaphragm vacuum sensor[3] and so on. As an example an inertia measurement system which operates as two-axis rotating gyroscope for navigation

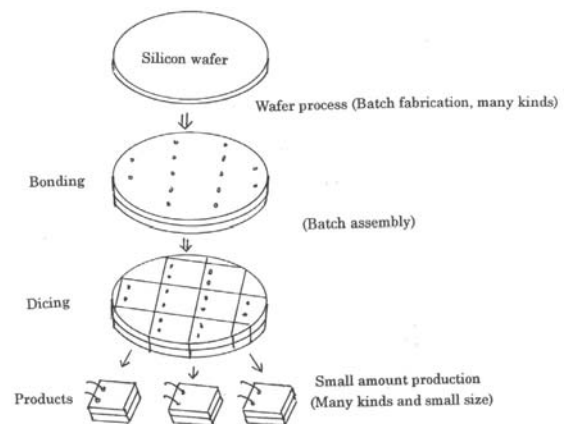


Fig.1 Wafer process packaging

control systems is shown in Fig.2 [4]. Since the rotor is electrostatically levitated this can be used as three-axis accelerometer as well[5][6]. The rotor of which diameter is 5mm was fabricated using the deep RIE of silicon. The levitation is actively controlled by force balancing in all direction using a capacitive displacement sensing and an electrostatic actuation. The rotation is based on the principle of a variable capacitance motor. The silicon rotor is packaged in a vacuum cavity by incorporating a non-evaporable getter in the cavity in order to prevent a viscous dumping[7]. The gaps between the silicon rotor and the electrodes on the glasses are $5\mu\text{ m}$.

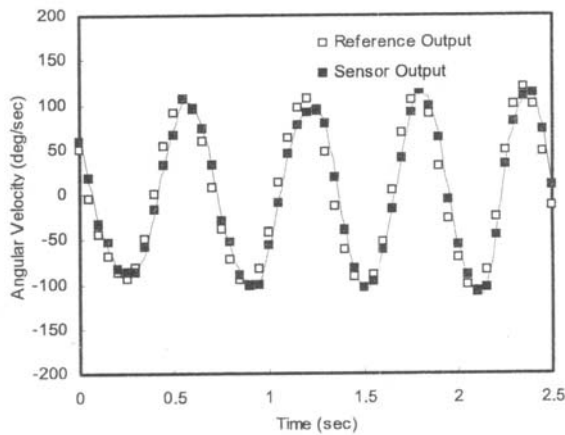
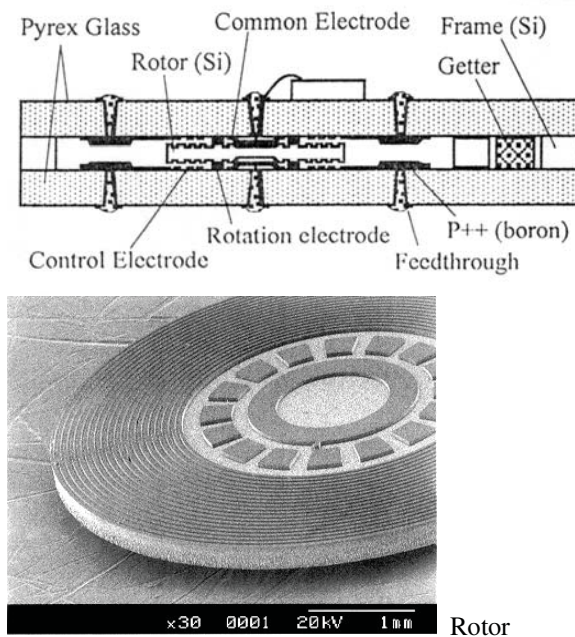


Fig.2 Electrostatically levitating micromotor and measured gyroscope response (Tokimec Inc. and Tohoku Univ.)

The levitated rotation (10,000 rpm) and the function as a gyroscope and an accelerometer were successfully demonstrated (Fig.2).

The electrical feedthrough in the glass can be made using a deep RIE (Reactive Ion Etching) of Pyrex glass and an electroplating of nickel[8]. Although the etching rate of the glass is not so fast ($0.5\mu\text{m}/\text{min}$), Pyrex glass could be etched through the thickness of $200\mu\text{m}$. Vertical etch profile could be obtained by narrowing the mask opening ($\sim 30\mu\text{m}$) because the deposition of non volatile products on the side wall is reduced. The holes made in a Pyrex glass was filled with nickel by electroplating as shown in Fig.3.

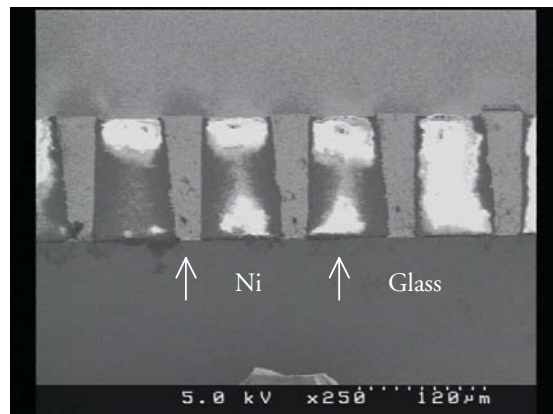
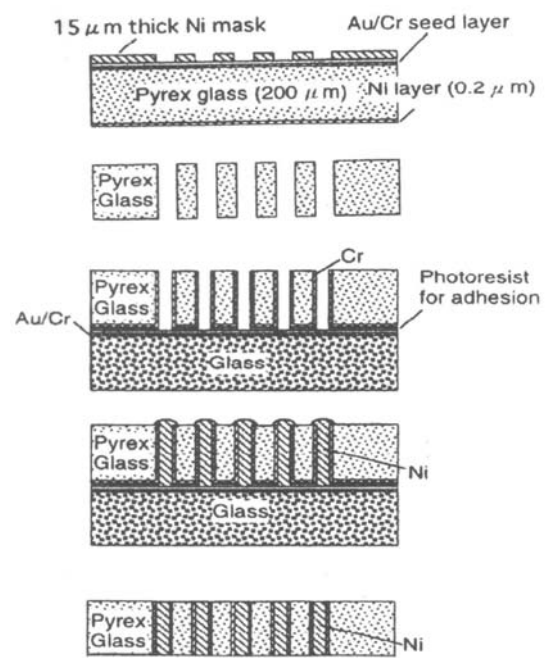


Fig.3 Electrical feedthrough in the glass made using a deep RIE and Ni electroplating

Fig.4 shows an application of the feedthrough shown in Fig.3. This is a micro relay which uses a bimetal actuator for making contact to the multi-micro spring[9]. The microsprings shown in Fig.4 have electrical connections to the backside of the glass. This electrical feedthrough can be also applied for multiprobe data storage and contactor for LSI probing which will be described later.

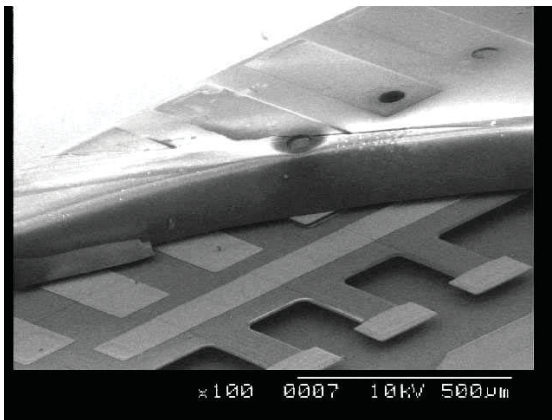
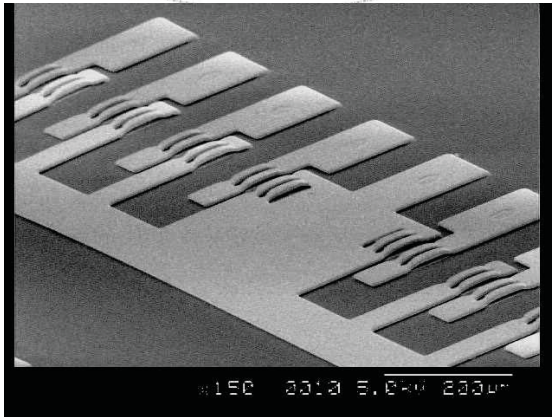
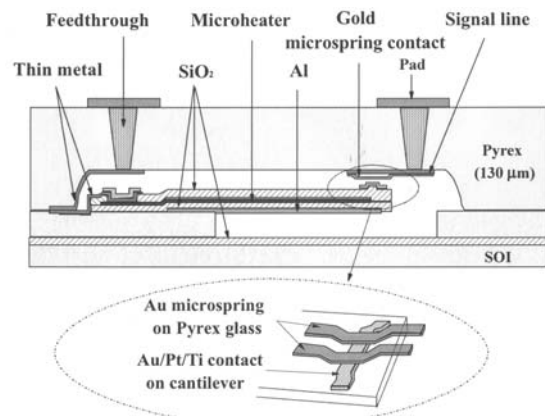


Fig.4 Micro relay having electrical feedthrough made by RIE and electroplating

MAINTENANCE TOOLS FOR EXTENDED LIFE

Active catheter

Multi-link active catheters which move like a snake in blood vessel have been developed for navigation in minimal invasive diagnosis and therapy. Distributed shape memory alloy (SMA) coils are utilized for the movement in multi-degrees of freedom.

Active catheters which have bending, torsional, extending and stiffness control functions are shown in Fig.5[10]. The SMA coil and a stainless steel liner coil are connected by nickel electroplating and acrylic resin deposition. This novel method enables low cost batch assembly and small outer diameter (1.4 mm).

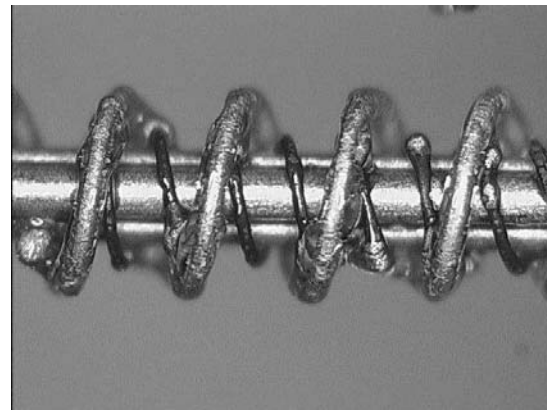
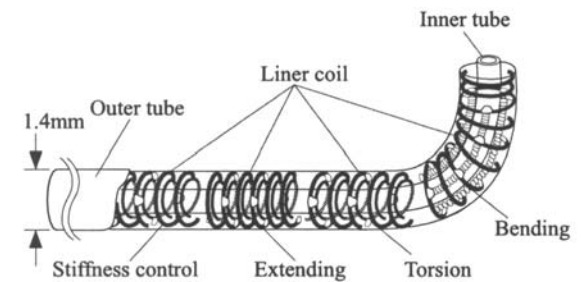


Fig.5 Active catheter which can not only be bent but also twisted and extended

Fiber optic pressure sensors

Small diameter ($125\mu\text{m}\phi$) fiber optic pressure sensor shown in Fig.6 has been developed for catheter use[11]. A thin diaphragm is formed at the end of an optical fiber and the deformation by a pressure is detected interferometrically. The diaphragm is formed on a silicon wafer and the wafer is etched by the deep RIE to make silicon rods having diaphragms. The silicon rod is bonded to the fiber end by heating in a glass tube. Finally the silicon is etched out using XeF_2

gas. By measuring the shift of the interference curve in wavelength axis the sensor was not influenced by the bending of the fiber.

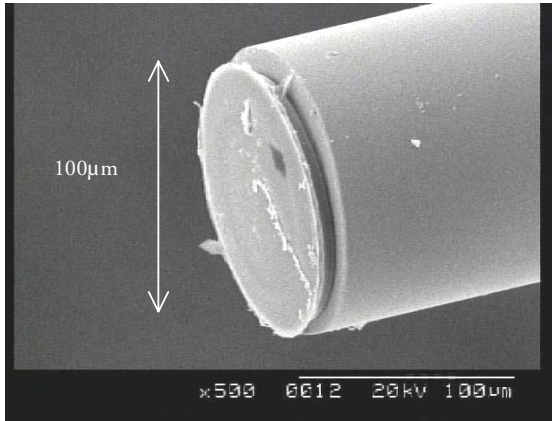


Fig.6 Fiber optic pressure sensor

Ultrasonic imager

A forward-looking ultrasonic imager has been developed[12]. A 1-3 composite piezoelectric PZT ceramic transducer array was made at the end of a catheter as shown in Fig.7. A receiver integrated circuit and a thermomechanical micro relay for multiplexing the transmitting high voltage pulse are under development to be assembled with the ultrasonic imager at the end of catheter.

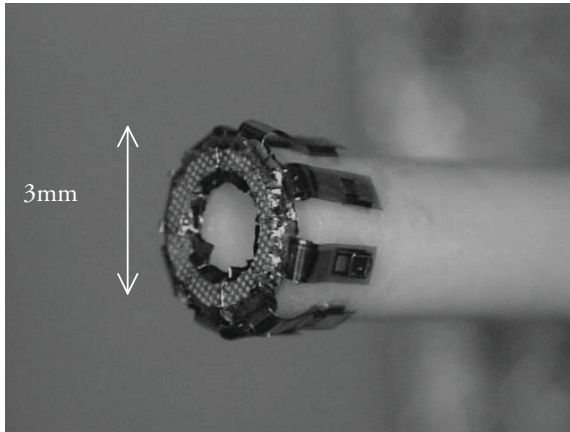


Fig.7 Ultrasonic imager at the end of a catheter

COMPACT POWER SOURCE

Micro air turbine

Silicon micro air turbine for rotating an integrated wire grid polarizer has been fabricated as a

polarization modulator needed for surface infrared adsorption spectroscopy[13]. The structure is shown in Fig.8. Air bearing is used and the rotational speed of 40,000 rpm was achieved. Based on this research micro gas turbine engine electrical power generators made of SiC are under development as shown below.

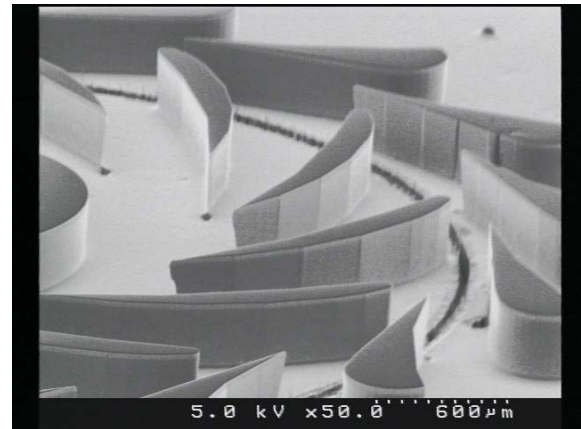
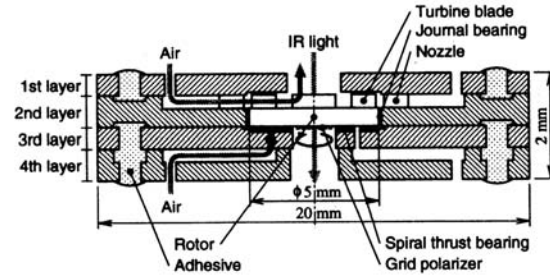


Fig.8 Silicon micro air turbine

Si lost mold process for SiC microstructures

Novel silicon lost mold process for ceramic microstructures has been developed[14]. A micromachined silicon wafer is used as a mould for sintering ceramics. The process to fabricate a SiC microstructure using silicon as a mold is shown in Fig.9. A silicon mould is formed by the deep RIE and is cast with slurry of SiC and carbon powder. SiC ceramic microstructures are obtained by a hot isostatic pressing (HIP) and finally the silicon mold is etched out. The process is called micro-reaction sintering because the silicon mold melts at the HIP condition (1700°C, 100MPa) and reacts with the carbon powder. Using this method SiC micro turbine for the purpose of micro gas turbine engine was fabricated as shown in Fig.9. The silicon lost mold process was also applied to fabricate PZT(lead zirconium titanate) ceramic microstructures[15].

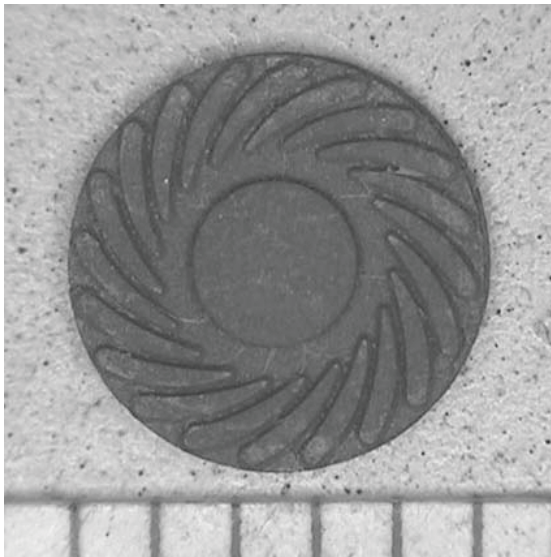
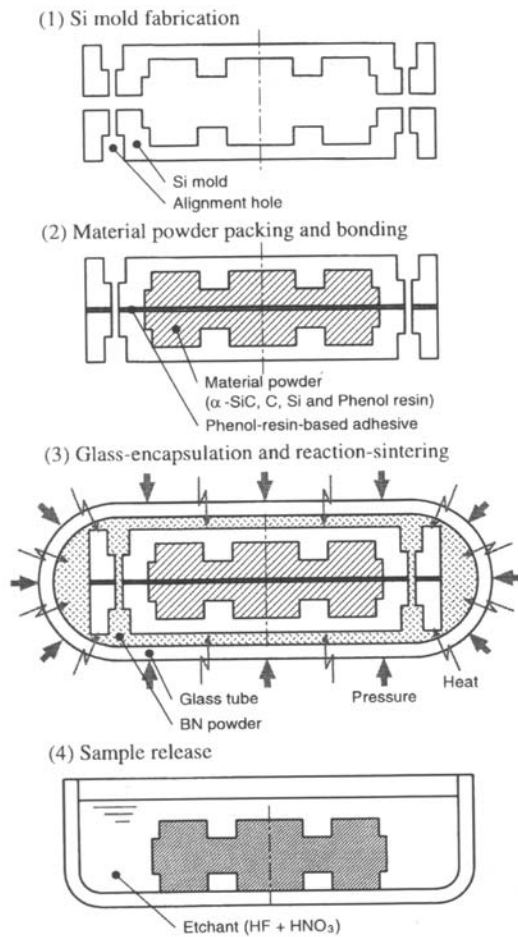


Fig.9 Si lost mold process for SiC and a micro turbine made by this method

Evaluation of hydrogen storage capacity of carbon nanotube by resonating thin cantilever

Thin silicon beams can be used as highly sensitive resonating sensors. Energy dissipation is reduced and Q (quality factor) higher than 200000 was obtained in vacuum after removing surface oxide by heating in ultra high vacuum(UHV)[16].

We applied the thin silicon cantilever to measure the hydrogen storage capacity of carbon nanotubes[17]. This is because carbon nanotubes have been attracted attentions for the application of reversible hydrogen storage for polymer electrolyte fuel cell. Fig.10 shows the carbon nanotube bundle attached on the end of a 170nm thick silicon cantilever. The frequency changes of the cantilever after loading the carbon nanotube and hydrogen adsorption are also shown in Fig.10. Hydrogen storage capacity of 6 wt% against the carbon nanotube weight was measured from the experimental results. The carbon nanotube can be selectively grown on a silicon cantilever using nickel catalyst[18].

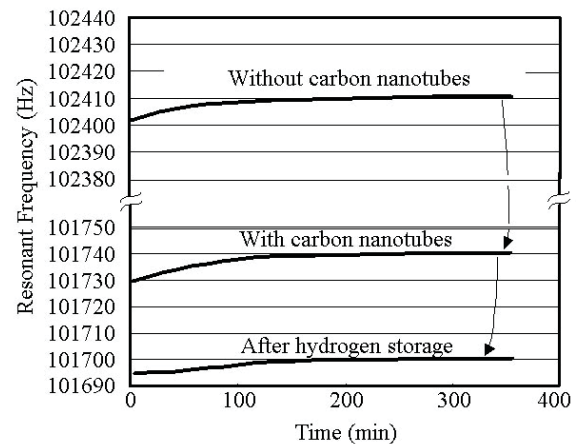
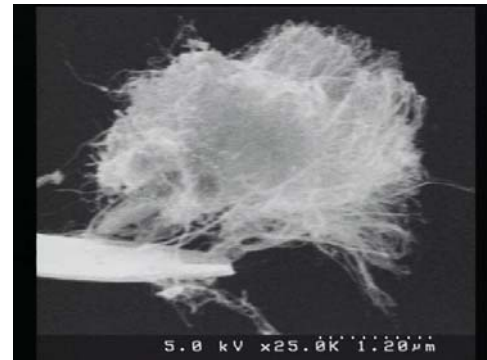


Fig.10 Carbon nanotube bundle attached on a silicon cantilever and the frequency changes of the cantilever after loading the carbon nanotube and hydrogen adsorption. The hydrogen storage capacity measured is 6 wt%.

MULTIPROBE DATA STORAGE

A microprobe which has a nano-heater with 30 nm metal junction located at the apex of a SiO_2 tip was fabricated as shown in Fig.11[19]. Not only high spatial resolution but also quick response can be achieved owing to the extremely small tip-size. Thermal processing for writing and electrical resistance measurement for reading was adopted for multiprobe data storage[20]. The structures of the multiprobe data storage system and the probe are shown in Fig.12. Self-actuating microprobe array can be made using AlN film as an actuator. The electrical feedthrough in a glass shown in Fig.3 is used to make an electrical connection from each probe to the backside IC chip. The electrical connection makes optimized process of the probe possible by separating the IC chip. This thermal nanoprobe could be successfully used for recording to the GeSbTe phase change recording media which is used for DVD RAM.

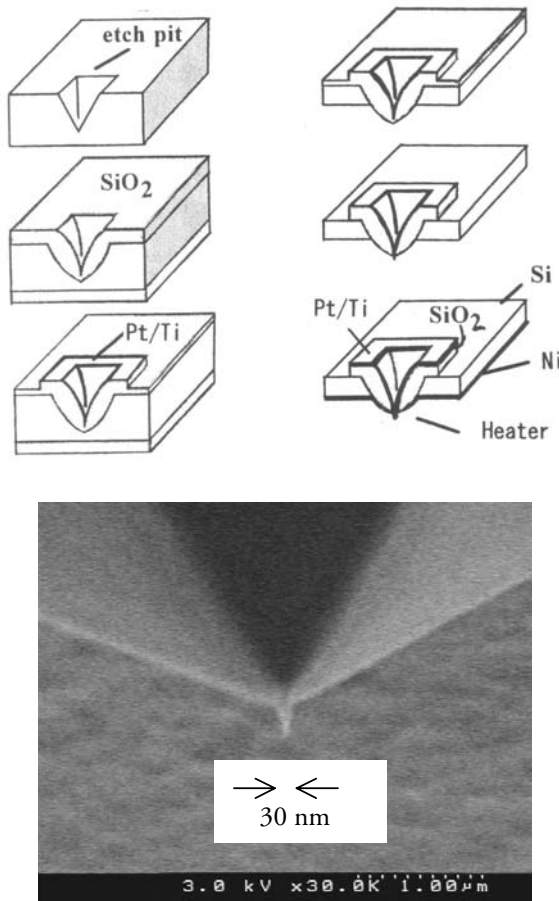


Fig.11 Fabrication process and a photograph of nano-heater

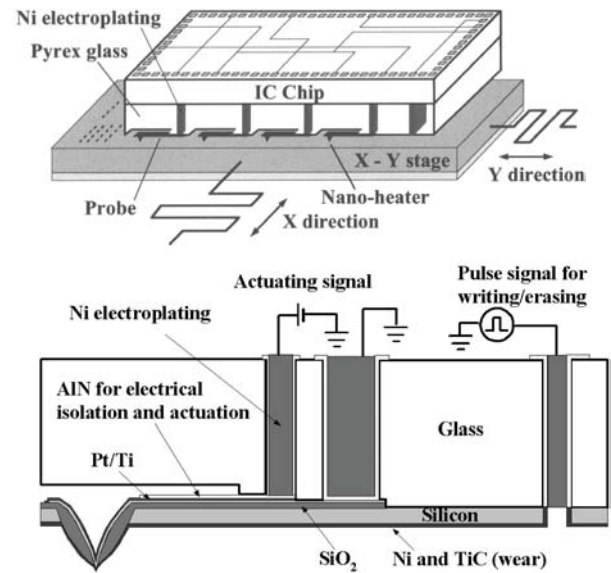


Fig.12 Structures of the multiprobe data storage system and a probe

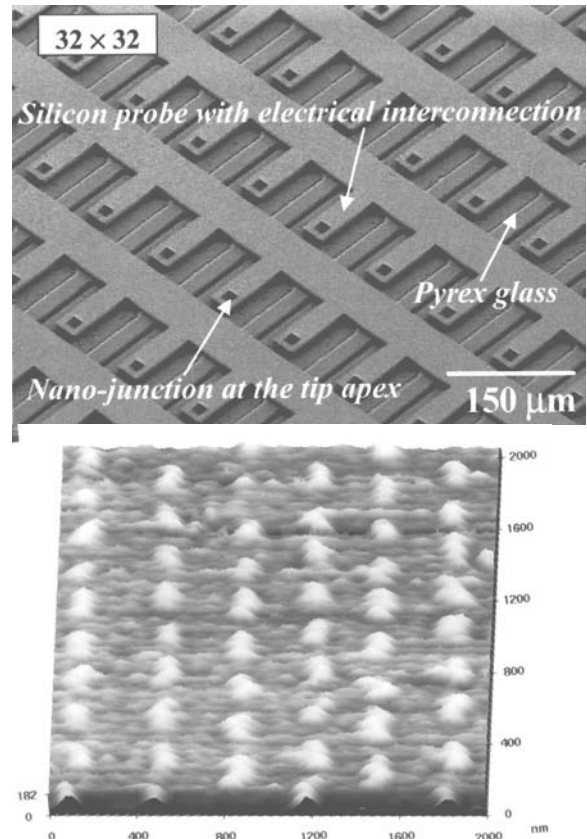


Fig.13 Nanoprobe array (32x32) and conductance image of the recorded bits on thin GeSbTe ($2\mu\text{m} \times 2\mu\text{m}$)

The nanoprobe 32×32 array and the conductance image of the recorded pattern are shown in Fig.13. The conductance modification of approximately ten times was caused by the phase change. Owing to the small (30nm) tip-size the bit density can be Tbit/inch² order which is about 100 times higher than the conventional data storage. Rewritable multiprobe data storage using the phase change media can be expected by making the thermal response of the probe quick.

KEY COMPONENTS FOR MANUFACTURING

Contactor for microprober

Micromachined contactor for microprober is shown in Fig.14 [21]. The electrical feedthrough made by deep RIE and nickel electroplating in the glass shown in Fig.3 plays important roles in the contactor. The bended silicon beams were fabricated by non-planer lithography by splay coating of resist and large focus depth projection exposure system (UX-2000 Ushio Inc.) and anisotropic silicon etching (p+ etch stop) after anodic bonding to the Pyrex glass.

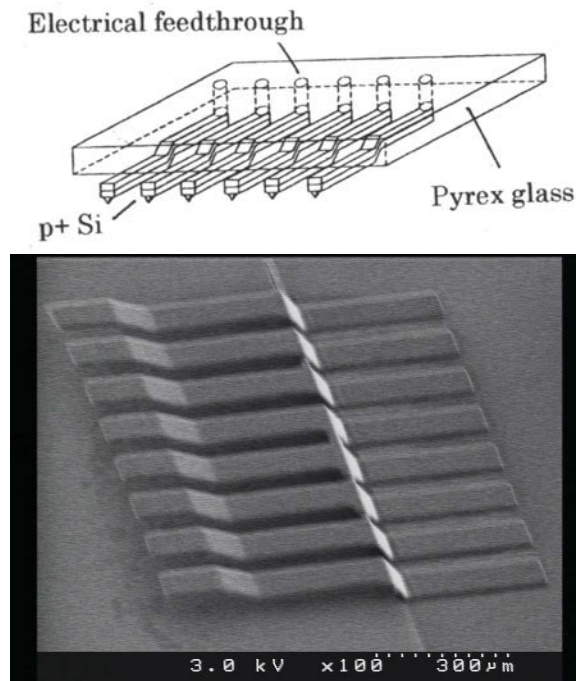


Fig.14 Contactor for microprober (Tokyo Electron Ltd. and Tohoku Univ.)

Anti-corrosive integrated massflow controller

Integrated massflow controller which has control valve and thermal massflow controller enables fine

gas control and minimized dead volume has been developed[22]. Fig.15 shows an anti-corrosive integrated mass flow controller made of stainless steel and AlN. The operation as the anti-corrosive massflow controller in chlorine gas was successfully demonstrated [23].

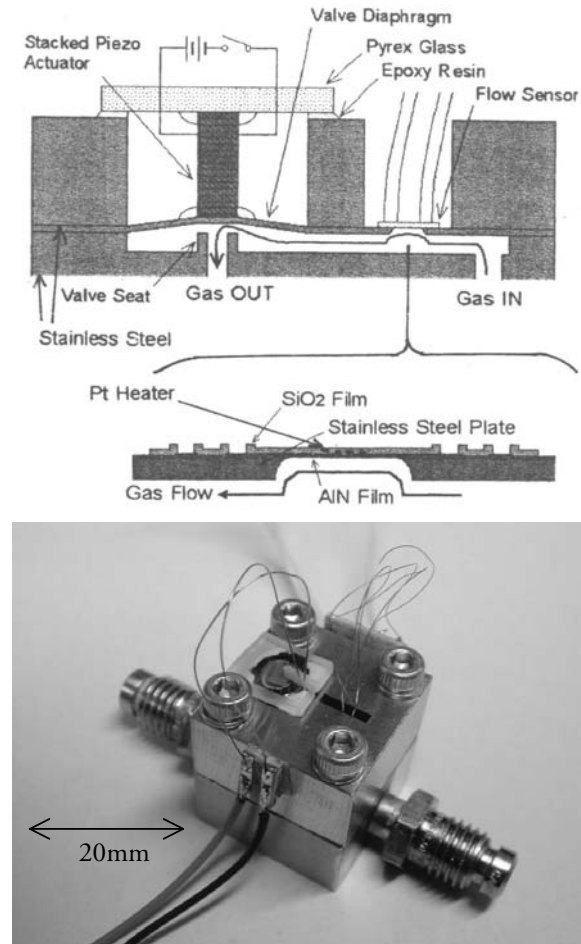


Fig.15 Anti-corrosive integrated massflow controller

CONCLUSIONS

Bulk micromachining with the aim of saving energy and natural resources has been described. Electrical feedthrough in glass holes has been applied to packaged micromechanical sensors. Maintenance tools as active catheters have been developed to be used in narrow space for extended life. Technologies for compact power source, multiprobe data storage and key components for semiconductor manufacturing have been developed. Nanometer structures could be extremely sensitive sensor and high density data storage.

ACKNOWLEDGEMENT

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REFERENCES

- [1] M.Esashi, "Encapsulated Micro Mechanical Sensors ", *Microsystem Technologies*, **1**, (1994) p.2
- [2] T.Kudoh, S.Shoji and M.Esashi, "An Integrated Miniature Capacitive Pressure Sensor", *Sensors and Actuators*, **A29**, (1991) p.185
- [3] H.Miyashita and M.Esashi, "Wide Dynamic Range Silicon Diaphragm Vacuum Sensor by Electrostatic Servo System", *J.Vac.Sci.Technology*, **B18**, (2000) p.2692
- [4] K.Fukatsu, T.Murakoshi and M.Esashi, "Evaluation Experiment of Electrostatically Levitating Inertia Measurement System ", *Technical Digest of the 18th Sensor Symposium*, (Kawasaki 2001) p.285
- [5] K.Jono, M.Hashimoto and M.Esashi, "Electrostatic Servo System for Multi-axis Accelerometers", *Proc. of MEMS'94*, (Oiso 1994) p.251
- [6] R.Toda, N.Takeda, T.Murakoshi, S.Nakamura and M.Esashi, "Accelerometer and Clinometer by Ball Micromachining", *Technical Digest of the 18th Sensor Symposium*, (Kawasaki 2001) p.279
- [7] H.Henmi, S.Shoji, Y.Shoji, K.Yoshimi and M.Esashi, "Vacuum Packaging for Microsensors by Glass-Silicon Anodic Bonding", *Sensors and Actuators*, **A43** (1994) p.243
- [8] X.Li, T.Abe and M.Esashi, "High Density Electrical Feedthrough Fabricated by Deep Reactive Ion Etching of Pyrex Glass", *Technical Digest of MEMS'2001* (Interlaken 2001) p.98
- [9] Y.Liu, X.Li, T.Abe, Y.Haga and M.Esashi, "A Thermomechanical Relay with Microspring Contact Array", *Technical Digest of MEMS'2001* (Interlaken 2001) p.220
- [10] Y.Haga, M.Esashi and S.Maeda, "Bending, Torsional and Extending Active Catheter Assembled Using Electroplating", *Proc. of MEMS'2000*, (Miyazaki 2000) p.181
- [11] T.Katsumata, Y.Haga, K.Minami and M.Esashi, "Micromachined 125 μ m Diameter Ultra Miniature Fiber-Optic Pressure Sensor for Catheter", *The Transaction of The IEE of Japan*, **120-E**, (2000) p.58
- [12] M.Nishio, K.Tani, Y.Haga and M.Esashi, "Preliminary Study of Integrated Ultrasonic Probe for Forward-Looking in Blood Vessel", *Technical Digest of the 17th Sensor Symposium*, (Kawasaki 2000) p.55
- [13] S.Tanaka, M.Hara and M.Esashi, "Air-Turbine-Driven Micro-Polarization Modulator for Fourier Transform Infrared Spectroscopy", *Technical Digest of the 17th Sensor Symposium*, (Kawasaki 2000) p.29
- [14] S.Sugimoto, S.Tanaka, J.F.Li, R.Watanabe and M.Esashi, "Silicon Carbide Micro-reaction-sintering Using a Multilayer Silicon Mold", *Proc. of MEMS'2000* (Miyazaki 2000) p. 775
- [15] J.-F. Li, S.Wang, K.Wakabayashi, M.Esashi and R.Watanabe, "Properties of Modified Lead Zirconate Titanate Ceramics Prepared at Low Temperature (800 °C) by Hot Isostatic Pressing", *J.American Ceramic Soc.*, **83**, (2000) p.955
- [16] J.Yang, T.Ono and M.Esashi, "Surface Effects and High Quality Factor in Ultrathin Single-crystal Silicon Cantilevers", *Applied Physics Letters*, **77** (2000) p.3860
- [17] T.Ono, X.Li, D.-W.Lee, H.Miyashita and M.Esashi, "Nanometric Sensing and Processing with Micromachined Functional Probe", *Technical Digest of the Transducers'01*, (Munich 2001) p.1062
- [18] H.Miyashita, T.Ono, P.H.Minh and M.Esashi, "Selective Growth of Carbon Nanotubes for Nano Electro Mechanical Device", *Technical Digest MEMS'2001* (Interlaken 2001) p.301
- [19] N.Takimura, D.W.Lee, M.N.Phan, T.Ono and M.Esashi, "Heater Integrated Micro Probe for High-Density Data Storage", *Technical Digest of the 17th Sensor Symposium*, (Kawasaki 2000) p.423
- [20] D.W.Lee, T.Ono and M.Esashi, "Fabrication of Microprobe Array with Sub-100nm Nano-Heater for Nanometric Thermal Imaging and Data Storage", *Technical Digest of MEMS'2001* (Interlaken 2001) p.20
- [21] T.Hoshino, S.Li and M.Esashi, "Basic Study of Micromachined Contact for LSI" (in Japanese), *Late news of 18th Sensor Symposium*, (Kawasaki 2001) p.63
- [22] M.Esashi, S.Eoh, T.Matsuo and S.Choi, "The Fabrication of Integrated Mass Flow Controller", *Technical Digest of the Transducers'87*, (Tokyo 1987) p.830
- [23] K.Hirata, D.Y.Sim and M.Esashi, "Stainless Steel-Based Integrated Mass-Flow Controller for Reactive and Corrosive Gases", *Technical Digest of the Transducers'01*, (Munich 2001) p. 962